

Supplementary information for ‘Quantized conductance in an InSb nanowire’

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1. Device fabrication and basic characterization

Contacts to the InSb nanowire were defined by electron beam lithography. Prior to metal deposition an in-situ argon etch was used to remove the native oxide around the InSb nanowire. Subsequently Ti (25 nm) and Au (150 nm) were deposited.

A gate trace taken with 10 mV DC bias at zero magnetic field (figure S1a) shows steplike features on top of a steep increase of current with gate voltage. Such steplike features have been observed in several devices and could be resulting from transport through individual subbands. Conductance traces at 0 T (see figure 3a of the main text) however do not show conductance steps, but instead show oscillations superimposed on an increase in conductance with gate voltage. Furthermore, we found that several wires with steplike features at $B=0$ T did not show conductance quantization at high magnetic field.

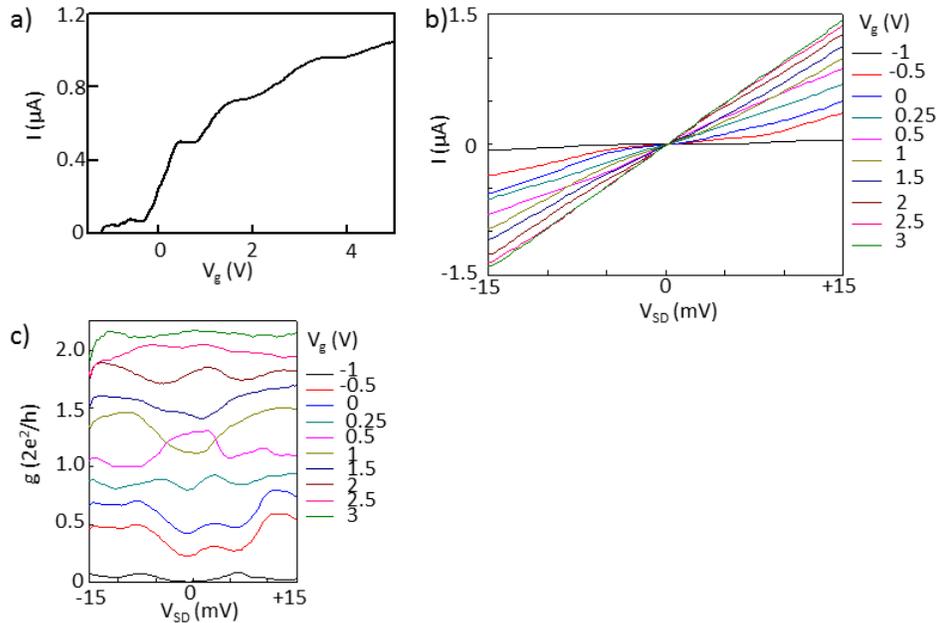


Figure S1. Electrical characterization device I. a) Pinch-off trace taken with 10 mV DC bias. As the current amplifier has a $2\text{k}\Omega$ impedance the minimum resistance of the wire and the wire-metal contact (at $V_g=5$ V) is $7.5\text{ k}\Omega$. b) Bias voltage sweeps at several gate voltages. c) Conductance as a function of bias voltage at several gate voltages. Conductance is obtained from a numerical derivative of the voltage sweeps shown in panel b. A vertical offset of $0.1g_Q$ is added between traces for clarity.

DC voltage bias sweeps show ohmic (linear) response at higher gate voltages (figure S1b). At gate voltages closer to pinch-off small deviations from ohmic response are observed with both increasing as well as decreasing conductance (see figure S1c, which is a numerical derivative of the data in figure S1b) for low bias voltages. Conductance measurements as a function of gate voltage and source-drain bias at zero magnetic field (figure S2a), where now an AC voltage excitation is used to obtain differential conductance, also show these oscillations. As both peaks and dips in conductance are seen these oscillations are not attributed to Coulomb blockade. While the origin of the oscillations is not entirely clear, we hypothesize it could be due to Fabry-Perot interference effects in wire regions¹, as sometimes a few periods of the oscillations are seen (such as in figure S2b and S2c). Another explanation would be the formation of resonances due to a confinement potential that is not sufficiently adiabatic along the direction of propagation².

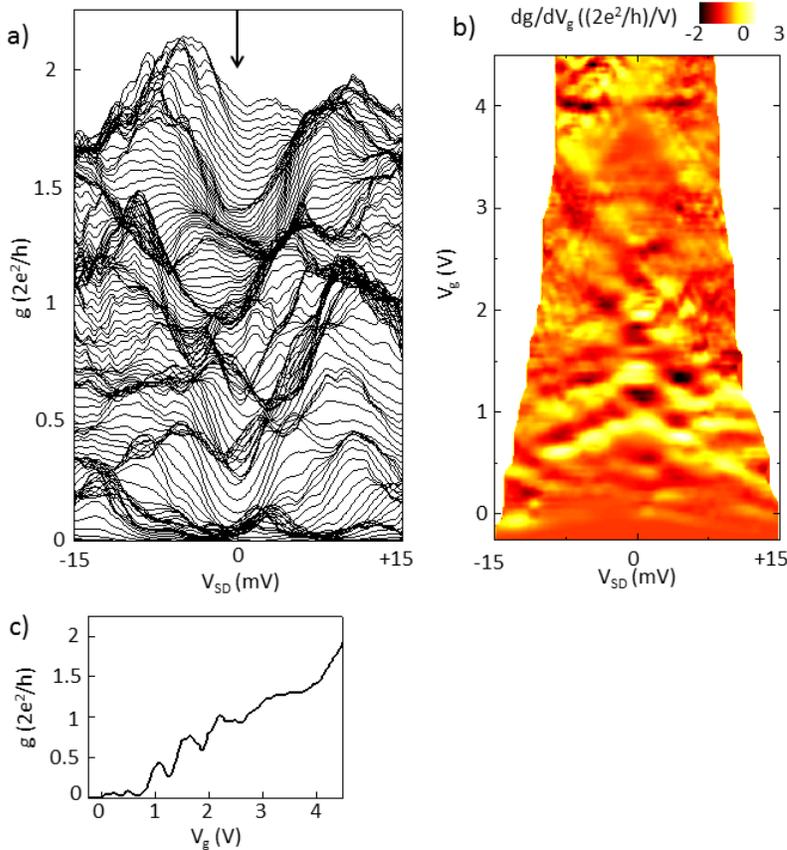


Figure S2. Voltage bias spectroscopy of device I at 0 T. a) Conductance g as a function of source-drain bias V_{SD} for fixed gate voltage in the range of -0.25 V to 4.5 V. No offset is added to traces. In the calculation of wire conductance a series resistance of $6\text{k}\Omega$ has been subtracted. Cut at $V_{SD}=0$ mV indicated by the arrow is shown in panel c. b) Transconductance dg/dV_g as function of source-drain bias V_{SD} and gate voltage V_g . c) Conductance as a function of gate voltage V_g at $V_{SD}=0$ mV.

The pinch-off trace of device II (figure S3a) also shows a steep current increase and steplike features. Small aperiodic oscillations are seen on top of the conductance gate trace at 0 T (figure S3b).

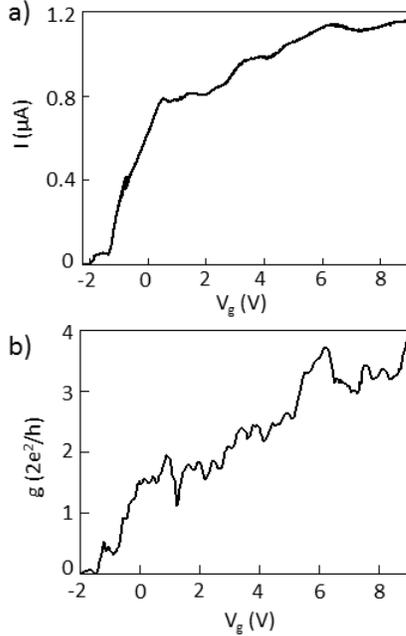


Figure S3. Gate traces device II. a) Pinch-off trace taken with source-drain bias $V_{SD} = 10$ mV. b) Conductance as function of gate voltage. $B=0$ T, $V_{SD}=0$ mV. A series resistance of 6 k Ω has been subtracted.

2. Contact resistance

For both device I and contacts 1-2 of device II 6 k Ω of resistance was subtracted in the conversion from current I_{AC} to conductance g , chosen such that the conductance of the second conductance plateau is $1.0g_Q$. The 6 k Ω series resistance consists of the impedance of the current amplifier (3 k Ω) and the resistance at the contact between wire and metal. The contact resistance is therefore taken as 3k Ω .

To examine whether 3 k Ω is a reasonable value for the contact resistance a comparison can be made to the resistance of the two devices at high gate voltage (high electron density). These minimum resistances were (after subtraction of ammeter impedance) 7 k Ω and 6 k Ω respectively and consists of both contact resistance and wire resistance. When also at high gate voltage a small number of subbands ($\sim \leq 10$) is occupied wire resistance still contributes significantly to the two-point resistance, and therefore the minimum resistance, although an upper limit, is not a direct measure of contact resistance.

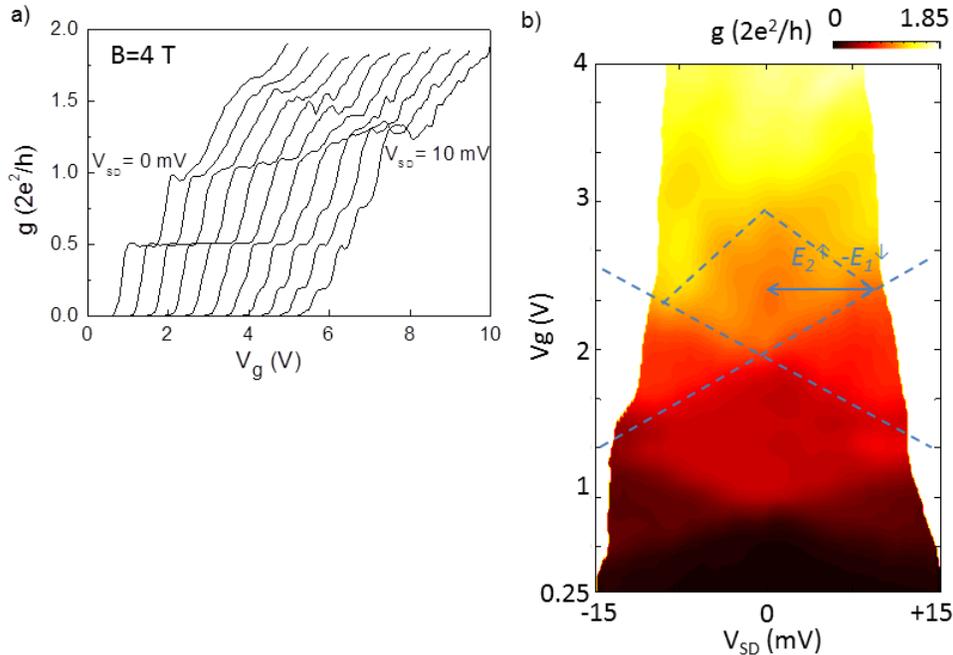
The assumption of a wire resistance contribution to the resistance at high gate voltage is supported by an estimate of the number of occupied subbands estimated from the electron density³ $n_{1D} \sim 4 \cdot 10^8 \text{ m}^{-1}$. In this calculation⁴ a 1D density of states with subband spacing derived from a cylindrical well with diameter 70 nm is integrated up to the measured density. Here we find 6 occupied subbands at high gate voltage, giving a contribution of

wire resistance $\sim 2\text{k}\Omega$ to the minimum resistance. Assuming a $2\text{k}\Omega$ wire resistance, the contact resistance would be $4\text{--}5\text{ k}\Omega$, close to the $3\text{ k}\Omega$ used in measurements.

For the wire region between contacts 2-3 of device II (see section 4 of the supplementary information) a smaller contact resistance was used ($1\text{ k}\Omega$ of contact resistance to match the conductance of the second plateau). For this device the minimum resistance at high gate voltage ($4\text{ k}\Omega$) was also lower than in device I and wire region 1-2 in device II, consistent with the assumption of a lower contact resistance.

3. Voltage bias spectroscopy $E_2^\uparrow - E_1^\downarrow$ of device I

The conductance of the $1.0g_Q$ plateau gradually increases to $1.25g_Q$ as source-drain bias is increased (figure S4a). The transconductance (Fig. 3c main text) therefore does not show a clear high-transconductance line separating the $1.0g_Q$ and $1.25g_Q$ plateau. This prevents extraction of subband spacing $E_2^\uparrow - E_1^\downarrow$ of device I from transconductance measurements. Instead the subband spacing $E_2^\uparrow - E_1^\downarrow$ of device I has been obtained from measurements of conductance as function of source-drain bias and gate voltage such as figure S4b. The transconductance of panel 3c of the main text is obtained from numerical differentiation of this conductance measurements to gate voltage.



S4. Voltage bias spectroscopy $E_2^\uparrow - E_1^\downarrow$ of device I. a) Gate traces at $B=4\text{ T}$ with increasing source-drain voltages. While the $0.5g_Q$ plateau shrink with source-drain bias, but remains at the same conductance, the conductance of the $1.0g_Q$ plateau at $V_{SD}=0\text{ mV}$ increases with source-drain bias. b) Conductance as function of gate voltage and source-drain bias at $B=4\text{ T}$. The approximate extent of the $1.0g_Q$ plateau is indicated.

4. Voltage bias spectroscopy of device II

The subbands spacings $E_1^\downarrow - E_1^\uparrow(B)$, $E_2^\downarrow - E_1^\downarrow(B)$ and $E_2^\uparrow - E_1^\uparrow(B)$ of panel 5b of the main text were obtained from voltage bias spectroscopy measurements. Similar to figure 4 of the main text, voltage bias spectroscopy measurement also here serve as a confirmation that the plateaux of device II seen in panel 5a of the main text are plateaux of quantized conductance, i.e. arise as a result of transport through separate subbands. Three of such measurements, at $B=3$ T, $B=5$ T and $B=9$ T are shown in figure S5, both as conductance traces as a function of source-drain voltage at fixed gate voltage (figures a, b and c) and transconductance representation (figures d, e and f). In the transconductance plots the plateaux with conductance $0.5g_Q$ and $1.0g_Q$ are indicated.

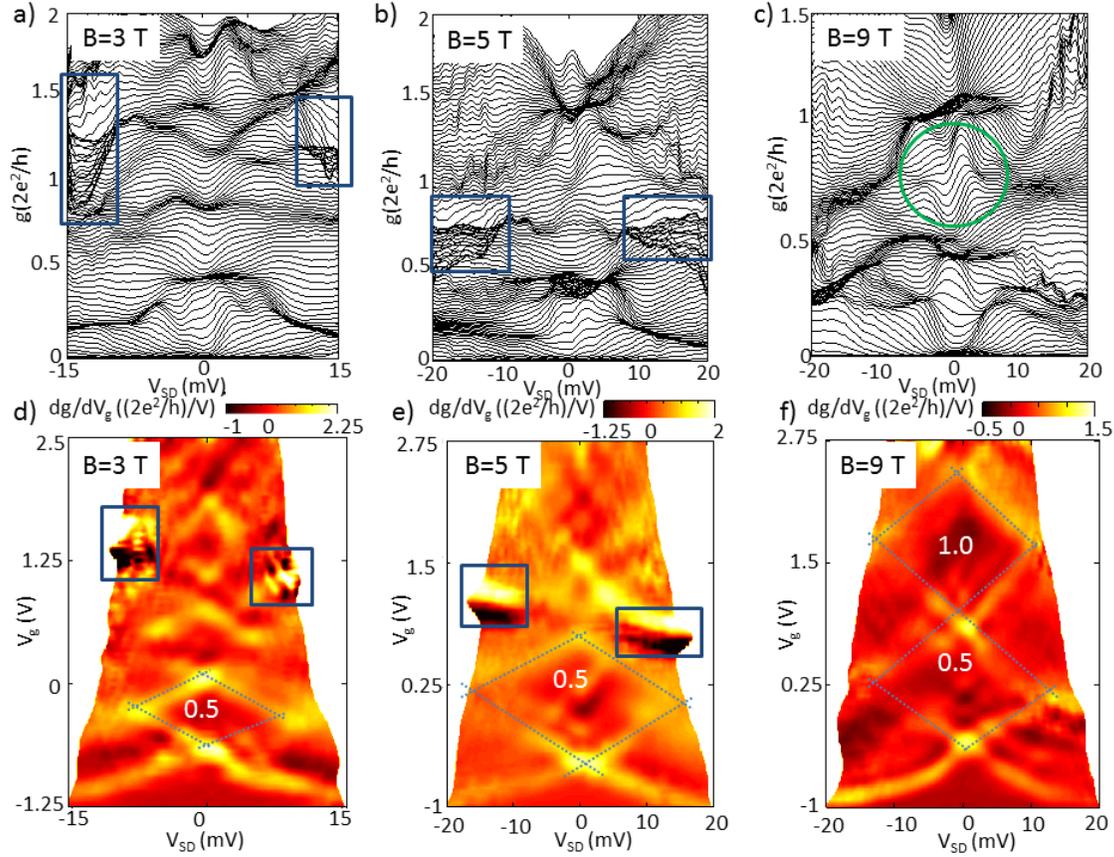


Figure S5. Voltage bias spectroscopy device II at $B=3$ T, 5 T and 9 T. a) (b),(c)) Conductance g as a function of source-drain bias V_{SD} for fixed gate voltage V_g in the range of $-1.25 \text{ V} \leq V_g \leq 2.5 \text{ V}$ at $B=3$ T ($-1 \text{ V} \leq V_g \leq 2.75 \text{ V}$ at $B=5$ T, $B=9$ T). Of the dense regions around $V_{SD}=0$ mV in panel S5a) only the plateau at $g \approx 0.5 g_Q$ has a constant conductance as a function of magnetic field, as seen in panel 5a) of the main text and in panels S5b) and S5c). In panel c) the conductance oscillations between $0.5g_Q < g < 1.0g_Q$ around $V_{SD}=0$ mV (indicated by the green circle) resemble Fabry-Perot interference. The deviations in the traces at high bias indicated by boxes in panels S5a) and S5b) are due to electronics artifacts. d) (e), f)) Transconductance dg/dV_g as a function of source-drain voltage and gate voltage. Conductance plateaux are indicated. Transconductance dips and peaks on conductance plateaux (seen for the $0.5g_Q$ plateau in panel e) and for the $0.5g_Q$

and $1.0g_Q$ plateau in panel f)) can be due to Fabry-Perot interference or resonances. Deviations in the regions at high bias indicated by boxes are due to an electronics artifact.

5. Subband crossing in wire region 2-3 of device II

Conductance quantization was also observed in the wire section between contacts 2 and 3 in device II (figure S6a). Similarly to the data shown in figure 5 of the main text the conductance steps also in this wire section are seen at $B \geq 2$ T ($g = 0.5g_Q$ plateau) and $B \geq 5$ T ($g = 1.0g_Q$ plateau). The transconductance of the gate traces shown (figure S6b) shows evidence of a subband crossing at ~ 4.5 T: the $0.5g_Q$ plateau remains constant in width for $B \geq 4.5$ T and the $1.0g_Q$ plateau widens for $B \geq 4.5$ T.

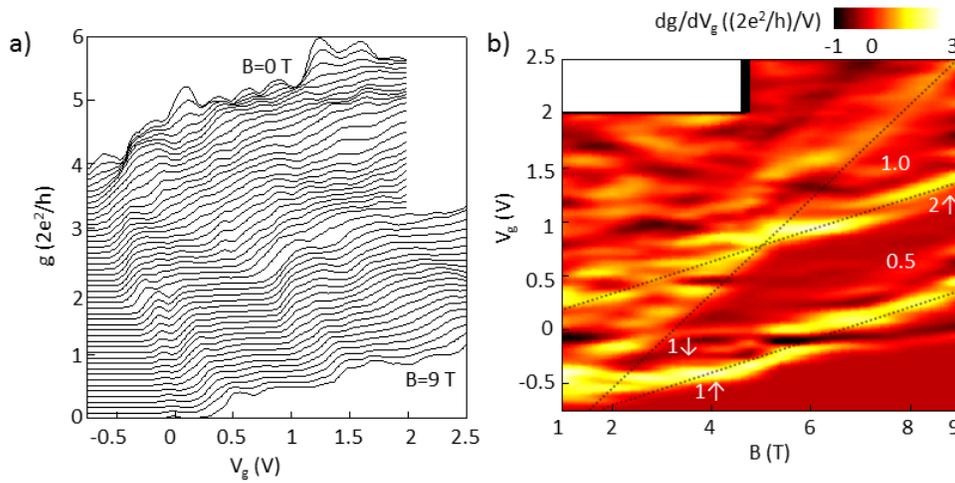


Figure S6. Subband crossing of wire region between contact 2 and 3 (inset panel 4a). a) Conductance as function of gate voltage V_g for out-of-plane magnetic field $B=0$ T to $B=9$ T in steps of 0.2 T. A series resistance of 4 k Ω was subtracted. b) Transconductance dg/dV_g of the data shown in panel a) in the range $B=1$ T to $B=9$ T. High transconductance (yellow/white) corresponds to the onset of transport through a subband. Conductance of the plateaux (zero transconductance; red) is indicated. Dotted lines are guides to the eye.

¹ Kretinin, A. V.; Popovitz-Biro, R.; Mahalu, D.; Shtrikman, H. *Nano Lett.* **2010**, 10(9): 3439-45.

² Tekman, E.; Ciraci, S. *Phys. Rev. B* **1989**, 39,12

³ Plissard, S. R.; Slapak, D.R.; Verheijen, M. A.; Hocevar, M.; Immink, G. G. W.; Van Weperen, I.; Nadj-Perge, S.; Frolov, S. M.; Kouwenhoven, L. P.; Bakkers, E. P. A. M. *Nano Lett.* **2012**, 12(4), 1794-1798.

⁴ Dayeh, S. A. *Semicond. Sci. Technol.* **2010**, 25, 024004.